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TRANSLATION

CONTROL OF GAS-TURBINE INSTALLATIONS

By

H. Ludwig

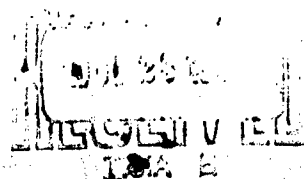
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CONTROL OF GAS-TURBINE INSTALLATIONS

H. Ludwig

Introduction¹⁾

The development and operation of gas-turbine installations is associated with, among other things, control problems. In this article the control processes that are applied to the various types of installations are discussed.

The control systems that are considered, comply exclusively to the data that are given in the literature. An attempt was made to produce a comprehensive and uniform illustration of the control system that is to be applied to gas-turbine installations.

1. Control of the Open Gas-Turbine Installation

1.1 Principles and Problems

The open gas-turbine installation operates according to the following principle: Air is drawn in through a compressor and compressed which is then heated in the combustion chamber. The gas-air-mixture that is obtained in this manner flows through a gas turbine, drives the compressor and the power-output machines to which it is also connected.

This principle of operation enables a great number of variations to be re-

1) Report from the VEB Research and Experiment Station for Jet Engines Dresden

alized. This consists in the application of several compressors and turbines in separate turbosets, by preheating the compressed air by the exhaust gases in the heat exchangers and by igniting other combustion chambers between the turbines. The closed cycle connections that are realized in this manner are quite numerous and have a considerable influence on the control process. Various demands are made of control depending, of course, on the required mode of operation of the installation, i.e., keeping it constant or changing certain entropies or the output. Certain fixed limitations with regard to revolutions, temperature and pressure must be maintained in the static state or in dynamic processes. In addition, the continuous combustion process must always be guaranteed.

The solution of these problems requires knowing the statistical control characteristics of the installations. In a simple case (Single-cycle installation) the combined compressor-turbine characteristic family gives some information on the cooperation between the two machines (fig. 1). The possible working points of this turboset are characterized by the following:

- a) the uniformity of the through put in connection with the same pressure ratio (disregarding fuel mass and pressure losses),
- b) balanced moments in the compressor and turbine, and
- c) fuel supply in order to attain the required gas temperature.

In this way load-line "a" is obtained for a turboset operating individually. If, at the same time, a working machine is driven by the turbine, then the position of the load line is a function of the turning moment/revolution of the turboset. In fig. 2 the effective moment of revolution is given as a function of the various gas temperatures in front of the turbine. In operating a working machine, the performance of which changes with the third power of the number of revolutions, the load-line moves toward "b" and toward "c" when a synchronous alternator (constant rpm) is operated. If the turbine is separated into two

mechanically independent parts, in which the one operates the compressor and the second which is the so-called power turbine drives the working machine, then there is no reaction in the characteristics of the working machine that now operates as a gas producing turboset in combination with the combustion chamber (fig. 3).

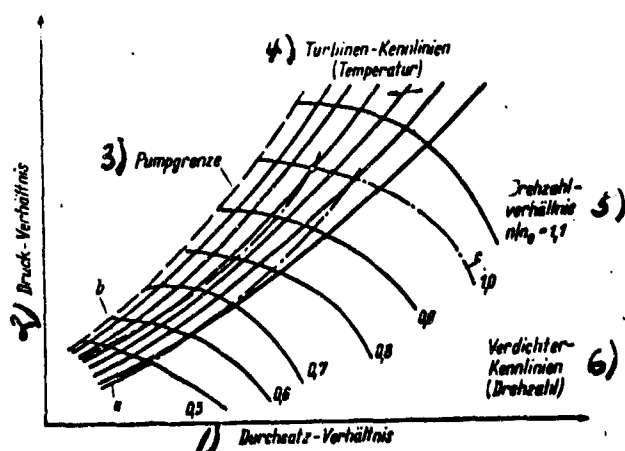


Fig. 1: Common Compressor-Turbine Family of Curves of a Single-Cycle Gas-Turbine Installation. Load-line a with a Turboset Operating Alone, b when Operating a Working Machine with Output = (rpm)³, and c when the Generator is Operated (constant rpm). 1) Throughput Ratio; 2) Pressure Ratio; 3) Pump Limit; 4) Turbine Characteristic Lines (Temperature); 5) RPM Ratio; 6) Compressor Characteristic Lines (rpm).

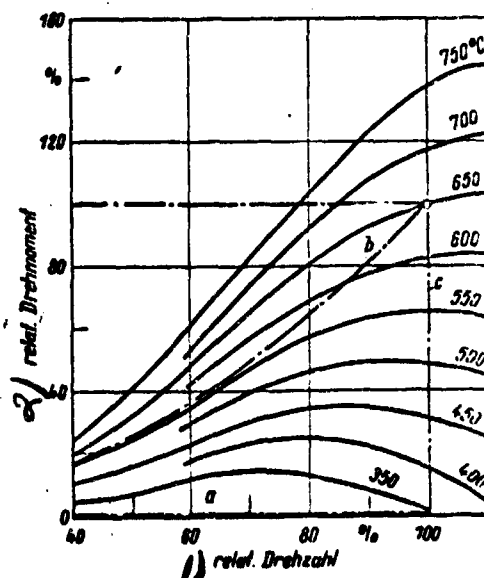


Fig. 2: The Pattern of the Effective Moment of Revolution of a Single-Cycle Gas-Turbine Installation, See fig. 1 for explanation of a, b and c. 1) Relat. RPM; 2) Relat. Moment of Revolution.

The determination or establishment of the load-lines for the entire installation as well as for the individual parts results in extensive thermodynamic calculations especially in connection with complicated closed-cycle connections. In order to determine the static behavior of the installation, as well as the adaptability of a specific application, the dependence of the decisive dimensions of the system is determined in the entire output range. In order to select a suit-

able type of installation, the rpm dependence of the effective moment of revolution is of fundamental importance in the output pattern in the operation of ship screws as well as in vehicles. The relationships between the adjustment, control and interference magnitudes can be determined from the characteristics of the installation. These, together with the control dynamic characteristics of the installation, form the principles for the selection of the control equipment and their characteristics.

The dynamic behavior of the gas-turbine installations as controls is characterized in the following manner. Each turbine installation has a certain amount of energy which is limited by various sources (potential heat energy in the air and gas spaces, kinetic energy in the rotating masses, thermal energy of all the mechanical installations, kinetic energy of the radiating energy carriers). The energy content is characterized in a specific installation by the entropy that appears which changes with output. Sudden changes in the energy that is supplied can, therefore, not lead to sudden changes in the energy output. Installations such as this are an advantage in that the change in the flow of energy is accompanied by only slight changes in the entropy of the energy reservoir of which is small. In the other cases the effect of the source must be reduced to a tolerable degree by means of special measures (e.g., auxiliary adjustment magnitudes). The following possibilities exist for this:

- a) Changing the transmission characteristics from the compressor to the turbine (blade adjustment),
- b) changing additional resistances in flow of the energy carrier "air" or "gas" (throttling),
- c) diverting the energy carrier "air" or "gas" to the turbine or combustion chamber, and
- d) additional inlet or outlet of the energy carrier "air" or "gas" or me-

chanical energy (braking or mechanical drive).

A change in the amount of fuel, first of all, changes the gas temperature. Since certain limits must be observed (temperature, pump, and flame-out limits), it is pointed out that the change in the energy inlet can take place at an arbitrary rate only within certain limits and beyond these critical values they must remain at specific relations to the compressed air that is supplied by the compressor. A change in the supply of compressed air due to a change in rpm of the compressor-device can, however, not result suddenly due to the mass moment of inertia. The control-dynamic behavior of the gas-turbine installation is essentially determined by this fact.

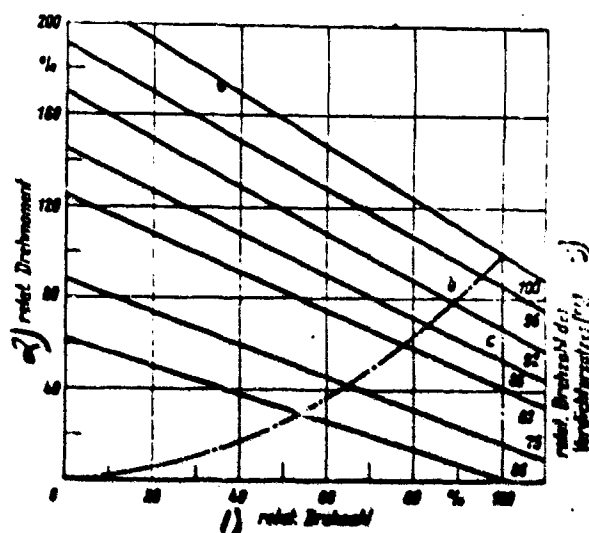


Fig. 3: The Pattern of the Effective Moment of Revolution of a Two-Cycle Gas-Turbine Installation with a Free Effective-Output Turbine. See fig. 1 for an explanation of lines b and c.

1) Relat. RPM; 2) Relat. Moment of Revolution; 3) Relat. RPM of the compressor set.

1.2 The Single-Cycle Installation

Single-cycle gas-turbine installations are used to drive electrical generators, to power locomotives and as air compressors in metallurgical plants (also as combined generator drive).

1.2.1 Generator Installations and Compressed-Air Supply Installations

In generator installations the fuel supply must be adjusted by a tachometer installation. In installations with air preheating it is often necessary to install pressure relief valves behind or after the combustion chamber, in order to prevent the rpm's from increasing (when the load is suddenly removed) which is usually controlled by the change in speed in the number of revolutions [2]. A temperature control installation is often installed in large units in front of or behind the turbine. In parallel operation with the circuit this can also be used as the main control equipment (the tachometer is a limit-regulating device) and certainly then the output. Control and regulating devices were also installed for limiting the temperature increasing speed which, to begin with permit, a certain jump in temperature and then the temperature increase and also the permissible increase in performance is limited per unit time [2] and [3].

The smaller and medium installations are almost without saying, equipped with fuel-air ratio limiting-control equipment which, during the starting process, prevent temperatures that are too high and pumping the compressor and in this way limit the starting time within the permissible minimal value. These devices are seldom used during normal starting instead of the temperature-limiting devices.

In metallurgical plants the gas-turbine installation is used to supply compressed air to the blast furnaces and often it is employed simultaneously to cover the electrical requirements. In the latter case, the regulation of the gas-turbine installation does not differ from that of the pure generator installations. The requirements for the operation of the blast furnace are fulfilled by a separate control of the compressed air cycle (fig. 4) [7]. When the gas-turbine installation is used only to supply compressed air it is then possible to adjust the control exclusively to this mode of operation [3]. The amount of air

that is supplied by the air compressor is controlled by the number of revolutions (fig. 4) [4] and [5].

An air-supply control adjusts the waste gas. The waste gas that is no longer required is again returned to the compressor inlet by means of an expansion turbine. Whereas in the installation that is under consideration (fig. 5) the air-supply control has a direct effect on the waste-gas supply, the theoretical value of the tachometer can also be adjusted. In the former case, the rpm adjusts in correspondence to the output balance (a tachometer is not required in normal operation). The range of operation of the installation must, however, be limited in relationship to the rpm, the gas temperature in front of the turbine and the pump limitation. In the first case, the pump limit-control equipment is used, as well as the temperature limiting control equipment. The theoretical value for the pump limiting control-equipment is adjusted as a function of feed pressure. The temperature limiting control-equipment is also geared to the control of the air-relief valve, while the rpm control equipment dominated the entire installation, the returned waste gas must be influenced by the air control installation.

1.2.2 Locomotive Installations

Single-cycle gas turbines with DC generators are used to power locomotives. The wheels are moved by series-wound motors. The regulation problems that appear are different than those that are encountered in stationary generator installations.

The generator load is determined by the motor current. This is a function of the power requirement of the locomotive on the circumference of the wheel or on the terminal voltage (excitation). In addition, the number of revolutions of the motor (running speed) is approximately proportional to the terminal voltage. The generator output (free gas-turbine output) is, on the other hand, a

function of the rpm of the gas-turbine installation and on the fuel supply. An economic run is subject to a certain correlation of the amount of fuel and number of revolutions as a function of performance [24].

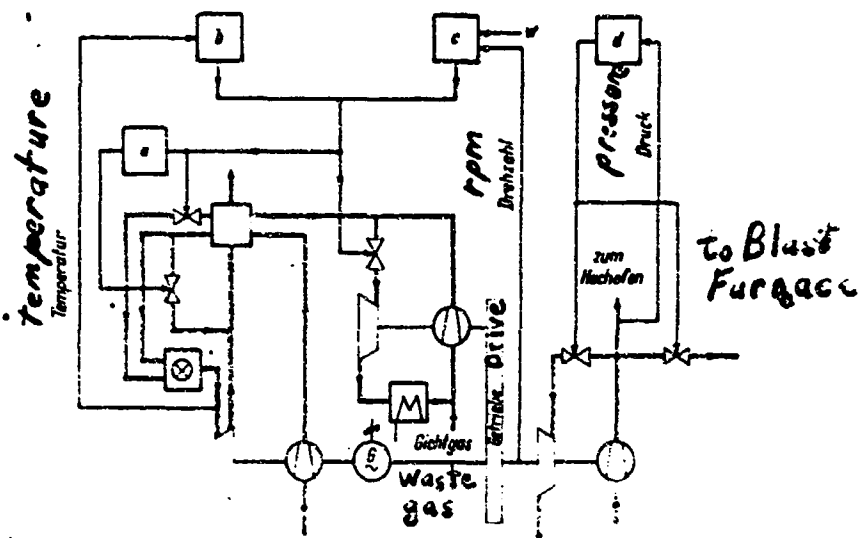


Fig. 4: Diagram of the Regulation of a Single-Cycle Gas-Turbine Installation for Generating Current and Supplying Compressed Air According to [5]. a is the blower control instrument, b the temperature regulating device, c tachometer, d pressure control equipment.

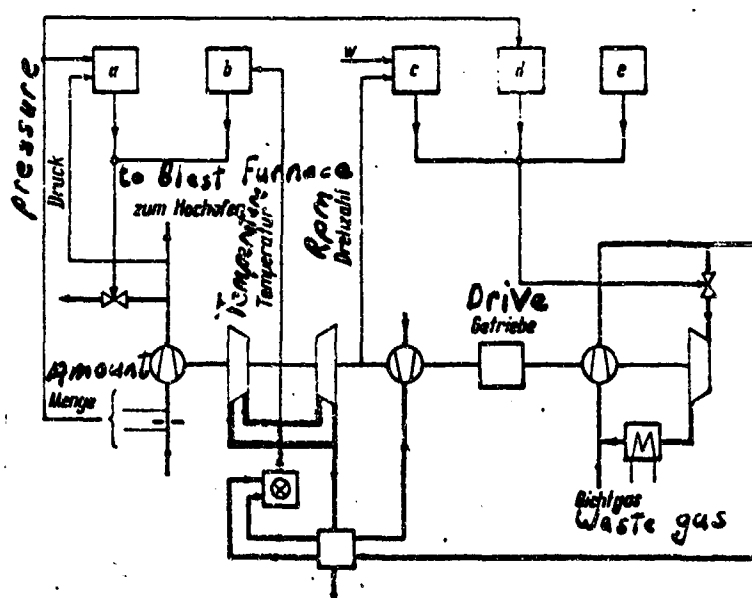


Fig. 5: Diagram of the Regulation of a Single-Cycle Gas-Turbine Installation for Supplying Compressed Air [4]. a limiting control equip., b temp. limit. regulator, c air-supply regulator, d air-supply regulat. equip., e control.

Maintaining this relationship, independent of external interference magnitudes to the locomotive, can be attained by a regulation system according to fig. 6. The manual adjustment of the power by means of the control instrument, determines the amount of fuel and the theoretical number of revolutions. A rpm control installation changes the load by adjusting the generator excitation in such a manner that the gas-turbine rpm is maintained constant. This eliminates the load changes which appear by changing the running requirements of the locomotive. The running speed, therefore, is dependent on the external interferences.

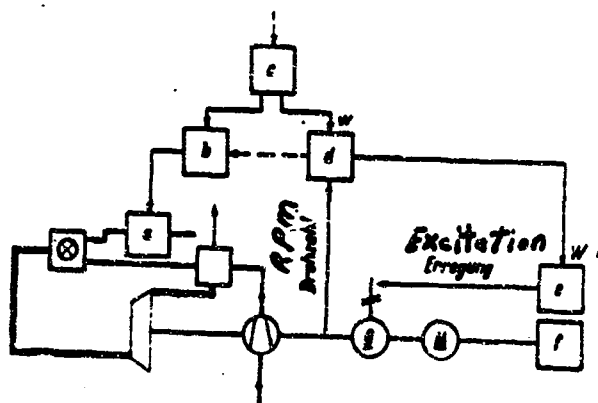


Fig. 6: Diagram of the Regulation of a Locomotive Gas-Turbine Installation. a) fuel system; b) fuel control, c) control device, d) tachometer installation, e) voltage regulator, f) wheel set for the locomotive.

If the excitation (running speed) and the theoretical rpm of the gas-turbine is fixed by means of the control instrument, then the external interference magnitudes lead to a decrease in the economical operation of the locomotive. If the permissible output is attained by the rpm that is set (temperature limitation), then the tachometer acts as a load regulating device with regard to the excitation [25].

Unsatisfactory dynamic characteristics result due to the rpm dependent performance setting in installations such as these. This deficiency is encountered in a regulation (fig. 6) in which the tachometer is adjusted to a theoretic-

al value, even temporarily, and that it affects the fuel system in such a way that a fast change in the number of revolutions is possible. Also in starting, when the field regulation device is off, the number of revolutions are controlled by the fuel system. It is possible to adjust the revolutions to the new value desired prior to the change in load, by means of a switch so that a change in performance can be attained through a fast change in temperature.

1.3 Two-Cycle Installation with the Free Power Turbine

In separating a turbine in order to produce the power, other possibilities present themselves in applying the installation to various operating conditions. The regulation of the rpm becomes significantly more difficult because the power device, generally, only has a slight amount of inertia and the storage effect of the compressor set, as well as the gas space (especially when an air preheater is employed) also materially worsens the transition behavior. This circuit is, therefore, only used when the generator installation must be kept within a favorable efficiency in the partial-load region, or when the installation is used for the direct operation of the propeller.

1.3.1 Generator Installations and Installations for the Supply of Compressed Air

In the generator installation the power turbine is equipped with a tachometer device which adjust the fuel supply. If the number of revolutions of the compressor turboset remains unregulated, then stability occurs independent of performance. Rpm limiting equipment are, not as a rule, provided for this cycle. An improvement in the regulation conditions can be obtained so that the compressor set is also equipped with a tachometer which adjusts the rated value of the revolution regulating equipment of the power turbine [5] to [7] (fig. 7).

A fast change in output as, for example, is necessary in connection with a great discharge in order to maintain certain critical values of the power-turbine

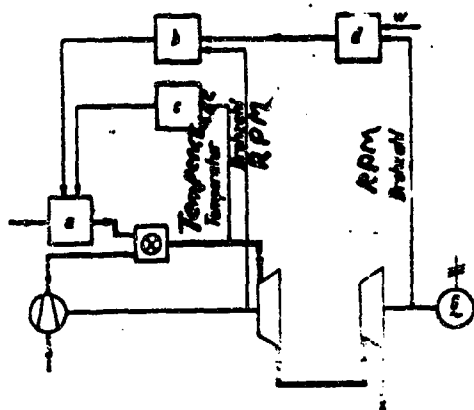


Fig. 7: Diagram of the Regulation of a Two-Cycle Gas-Turbine Installation with Free Power Turbine According to [5] and [7]. a) fuel system, b) tachometer, c) temperature limiting regulator.

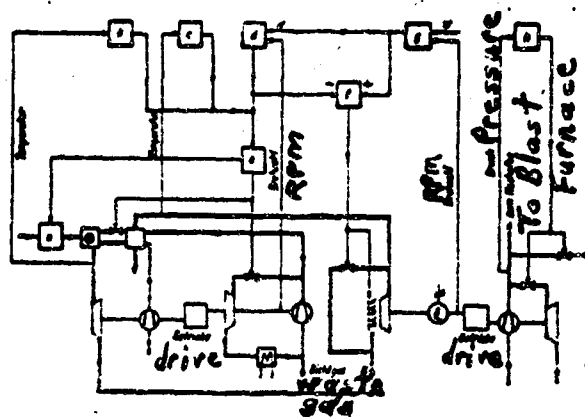


Fig. 8: Diagram of the Regulation of a Two-Cycle Gas Turbine Installation with Free Power Turbine According to [11]. a) fuel system, b) temperature limiting regulator (high-pressure), c) as b) (low-pressure), d) tachometer (high-pressure), e) switching equipment, f) control device, g) as d) (low-pressure), h) pressure regulator.

rpm, is difficult to realize. In addition to the adjustment of the amount of fuel injected, valves are also often opened in front of the turbines or in front of the combustion chamber by the tachometer when the revolutions increase too much [8] and [9]. Another possibility, but very seldomly used method, is in increasing the inertia of the power device by means of a flywheel [10].

Another possibility of intervention is presented by the arrangement of adjustable guide vanes in front of the power-turbine. When the entrance vanes are opened the rpm of the compressor set increases and the power stage of the power-turbine decreases.

The installation that is illustrated in fig. 8 [5] and [11] in addition to being used for the generation of electricity, can be used simultaneously to

supply compressed air to the blast furnaces in a metallurgical plant. The tachometer (low pressure) that is provided to control the revolutions of the power turbine, produces the controlling magnitude as the output magnitude for the tachometer installation for the high-pressure set. This controls the fuel supply and, at the same time, can also effect the entry fans of the low-pressure turbine. The adjustment of the entrance vanes is, in addition, directly associated to the tachometer installation (low pressure) as a position magnitude. In order to control the number of revolutions of the low-pressure turbine by removing the load, by-pass valves are opened by the two tachometer installations in the low-pressure turbine. In addition, limitation devices are actuated when required by the gas temperatures in front of the high-pressure turbine and, in the fuel control according to the low-pressure turbine.

1.3.2 Marine Power Plants

Installations with a free power turbine were always used in ships for the direct operation of the propellers because of the requirements for the method of operation. Because of the strong automatic regulation effect of the screws, as well as the absence of essentially haphazard interferences, the tachometer installation can be eliminated and only limiting installations need be dealt with that suitably limit the revolutions and the temperature. The power is adjusted manually according to the navigation requirements [12].

Special problems are created in connection with reversing. Adjustable pitch propellers or a reversing gear is employed with flow-coupling, or torque converter. The correct filling or discharging is provided by the control equipment [13] and [14].

The control of an installation with variable pitch propeller is illustrated in fig. 9 [15] and [16]. The power is adjusted by means of a tachometer installation for the compressor set and a control device to vary the pitch of the guide

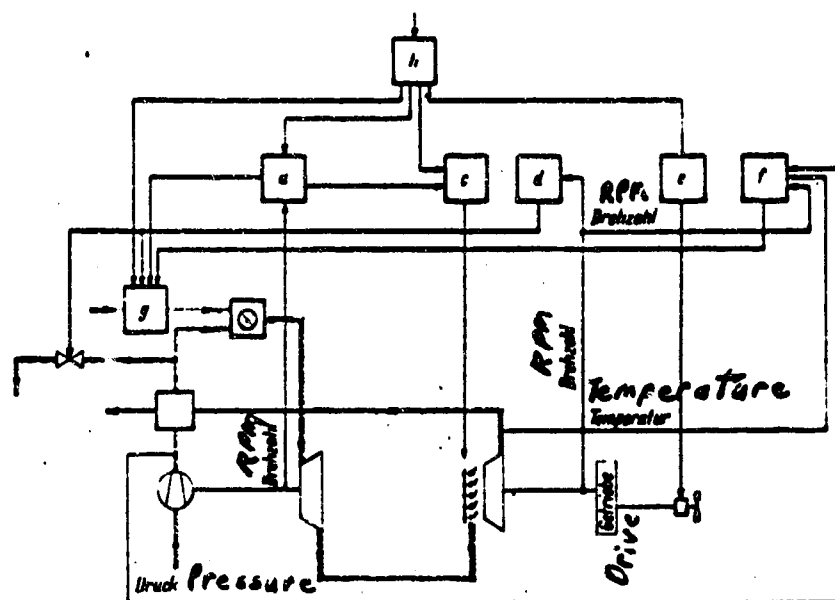


Fig. 9: Schematic Diagram for the Regulation of a Ship's Gas Turbine Installation According to [16]. a) is the tachometer installation, c) the guide vane control, d) rpm limiting installation, e) ship's screw control, f) temperature control installation, h) control device, g) fuel system.

Special requirements appear due to maneuvering conditions. Here too relief valves are used in front of the power turbine in the event unsatisfactory conditions are met.

vanes of the power turbine. By means of the central control equipment the critical value of the number of revolutions of the compressor is determined.

This critical value remains constant in the lower performance range and an increase in performance is introduced by the central control device by closing the guide vanes.

In so doing the speed regulating device increases the amount of fuel in order to maintain the critical value. In this method of moving it is possible to disregard the best possible efficiency without losing time to accelerate the compressor set to attain about the half of its maximum output. In the upper performance range the critical rpm value is increased. The speed regulating device, however, now adjusts the guide vanes, whereas the increase in the amount of

1.4 Two-Cycle Installations in Parallel Connection-Circuits

The especially unsatisfactory regulation dynamic characteristics of the gas-turbine installations with free power turbines are eliminated in the connection-circuits in the operation of electrical generators. In this case, the power turbine powers a compressor simultaneously with the generator. In so doing the inertia of this device is increased together with the automatic regulating effect.

The regulation of an installation in parallel connection with a power turbine take-off on the low-pressure shaft is illustrated in fig. 10 [26]. The air throughput is essentially determined by the revolutions of the low-pressure shaft. Since the revolutions must be kept constant, the change in performance is attained, above all, by changing the temperature of the gas.

The main regulation variable is the rpm of the low-pressure shaft. The speed regulation device consists of two-position settings by which the fuel supply to both combustion chambers is adjusted according to a prescribed correlation.

The high-pressure turboset is adjusted on the basis of the inherent stability in the entire load range to a revolution that is a function of the performance and it is not regulated. Only when the speed increases unduly is the speed-regulating device engaged, reducing the fuel supply to the high-pressure combustion chamber.

When the gas temperature in front of the high-pressure turbine attains the high-temperature permissible in the upper performance range, the high-pressure temperature-limiting regulator over rides the low-pressure speed regulating device and takes over the adjustment of the fuel supply to the high-pressure combustion chamber. In parallel operation with the circuit it is also possible to adjust the gas temperature in front of the low-pressure turbine by the low-pressure temperature limit-regulator by adjusting the fuel supply for the low-pres-

sure combustion chamber and it can be kept at its maximum value. The low pressure speed regulating device then operates as a limit regulating device and the installation continues to operate at its maximum output.

2. Regulation of the Free-Piston Gas-Turbine Installation

The free-piston gas turbine installation corresponds in its basic design to the open gas-turbine installations with the free power turbines. The free-piston gas generator (fig. 11) takes the place of the compressor, combustion chamber and turbine.

2.1 Regulating the Gas Generator

In addition to the regulating problems that occur initially in the operation of the entire installation of free-piston gas turbines, to begin with, fundamental problems of controlling the gas generator alone are to be solved. In order to stabilize the movement of the piston of the gas generator it is necessary that the processes in the Diesel engine are adjusted to each other in the air compressor and in the buffer spaces. The assumptions that are required are given, to begin with, by the constructional dimensions. The determining dimensions of the piston stroke and frequency for the amount of fuel that is supplied is in a specific relationship to the other dimensions of the gas generator (engine compression, gas pressure or scavenging-air pressure, as well as the mean air pressure in the buffer space) (fig. 12) [17] and [27]. One can see from this description that in order to produce a specific amount of gas there must be a suitable combination of stroke and frequency with a stipulated gas pressure not only a possibly stable working point but there must also be an entire working scope. In order to obtain an exactly defined operating law for the gas generator, the piston stroke and the frequency must be determined for each value of the gas pressure. In general, the determination is obtained in

such a manner that the engine compression attains the maximum value when the gas supply is at full-open throttle and in idling, the smallest possible value is assumed. As may be seen from fig. 12, maintaining a specific engine compression is a function of the gas pressure and piston stroke, and maintaining a specific temporary average-pressure in the buffer space. This pressure is dependent on the amount of air captured in the buffer space. Since, however, this is independent of the processes in the propellant-gas generator, the necessity of introducing a regulator can be seen in order to realize the operating law that was established.

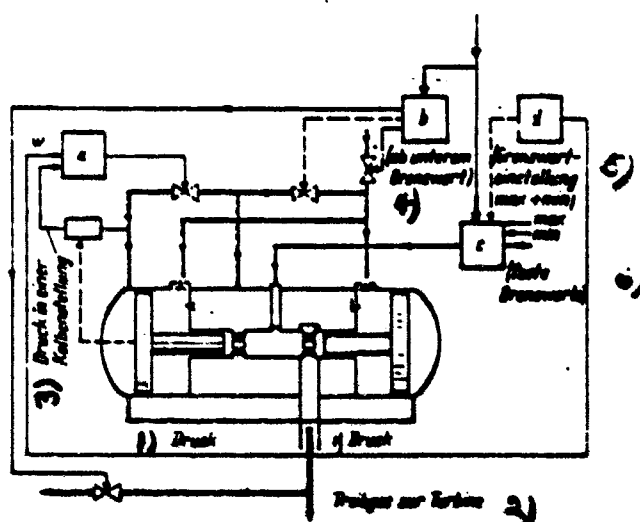


Fig. 11: Diagram of the Internal Regulation of a Free-Piston Gas Generator.

- a) pressure regulator, b, d) control device, c) fuel system.
- 1) Pressure; 2) propellant gas to the turbine; 3) pressure in a piston position;
- 4) (from the lower critical value); 5) (critical value adjustment max + min);
- 6) (fixed critical value).

In order to accomplish this a pressure regulator is used (stabilizer) which regulates the buffer-space pressure in connection with a specific piston position or the temporary average pressure in the buffer space as a function of the determining value of the propellant gas or scavenging pressure. The relationship between these two pressures is selected linearly. By using a pressure

regulator the desired increase in the engine compression is attained as a function of the gas pressure and the piston stroke [18]. The amount of adjustment of the pressure regulator must supply the required amount of air to or from the buffer space. Since the scavenging pressure during the course of a piston stroke is partially above or below the buffer pressure it is most easily accomplished with the aid of a final control element. This pressure regulation is illustrated in the diagram for the entire internal regulation of a gas generator (fig. 11). Certain critical values are obtained for the piston stroke by means of the structural dimensions. With the smallest stroke the distance of the top dead-center must still be great enough so that the inlet port of the Diesel engine is kept sufficiently clear in order that even with the greatest stroke, this value must still be sufficiently small to prevent the cylinder head from being struck. The position of the bottom dead center and, consequently, the stroke length itself, as well as all the other internal dimensions are determined by the mode of operation of the pressure regulating equipment in which every value of the top dead center is a function of the fuel pressure. The amount of fuel is also clearly correlated with the gas pressure and the position of the top dead center. In order that the boundary of the top dead center is not exceeded it is necessary to extend the internal regulation in order to control the maximum permissible value for the fuel supply, as a function of the gas pressure (fig. 11). After the amount of fuel changes a transition results in the gas generator in the new final state according to the following cycle: increasing the amount of fuel - increasing the piston stroke - increase in the amount of air and propellant gas - rise in gas pressure - increasing the amount of air in the buffer space by means of the pressure regulator - increasing the frequency - additional increase in the amount of air - increasing stabilization until a new value is attained for the piston stroke, frequency and gas pressure. Since several reservoirs must

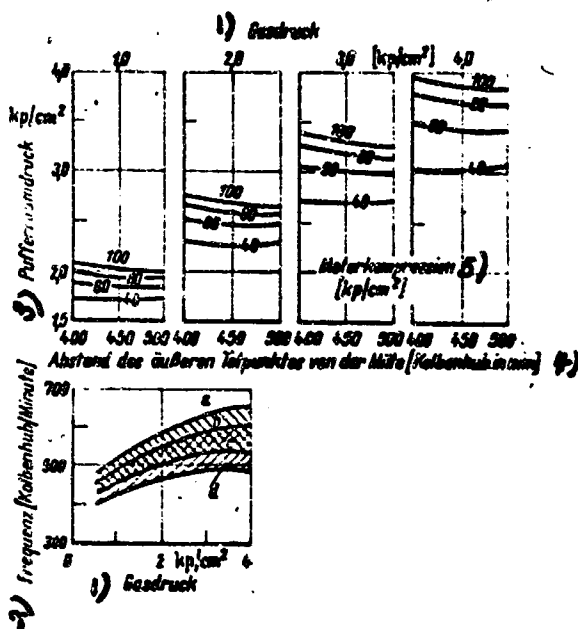


Fig. 12: Pressure Diagram for a Free-Piston Gas Generator.

- a) Maximum engine compression, minimum stroke
- b) Maximum engine compression, maximum stroke
- c) Minimum engine compression, minimum stroke
- d) Minimum engine compression, maximum stroke
- 1) Gas Pressure; 2) Frequency [Piston Stroke/Minute]; 3) Buffer Space Pressure;
- 4) Distance of the top dead center from the middle [Piston Stroke in mm];
- 5) Engine Compression.

be charged or discharged in this operating cycle, the transition behavior of the gas generator is characterized by a corresponding time delay. The change in the amount of fuel can, therefore, be adjusted suddenly only to the value that was established by the critical value control. The continued process then takes place corresponding to the change in gas pressure in units of time.

These boundary conditions, therefore, have the same effect as does the temperature or pump limitation in the standard gas-turbine installations.

In addition to the limitation in the amount of fuel that is dependent on this operation condition, care must, however, still be taken that the maximal and minimal, especially the permissible amounts of fuel cannot be exceeded or fall short.

When the piston stroke is minimal and the fuel amount is minimal the result-

ing amount of gas is still greater than is necessary to operate the gas turbine under no-load conditions. An additional reduction in the stroke of the piston or the frequency is either subject to a reduction in the distance of the top dead center or an increase in the distance of the bottom dead center of the piston movement. Both, however, are not permissible and is prevented by the above described control in critical value. In order, however, to also be able to operate the entire installation in the range between the lowest bottom dead center of the gas generator (about 20 ... 30%) and the no-load condition of the turbine, it is necessary to let the initial magnitude for the gas generator in the lower performance range to act on an auxiliary internal control installation and not on the fuel supply. The following possibilities can be used for this (fig. 11) [18]:

- a) Control of a gas-release valve,
- b) Control of a return valve in a connecting line between the scavenging-air housing and the air inlet on the compressor, and
- c) Control of a throttle valve on the compressor inlet.

Design a) is accompanied by a very poor no-load fuel consumption, whereas in design b) an essential reduction is attained. This is especially true in installations for vehicles. Design c) is not always easy to realize technically, because between the two compressors a complete balance must be achieved.

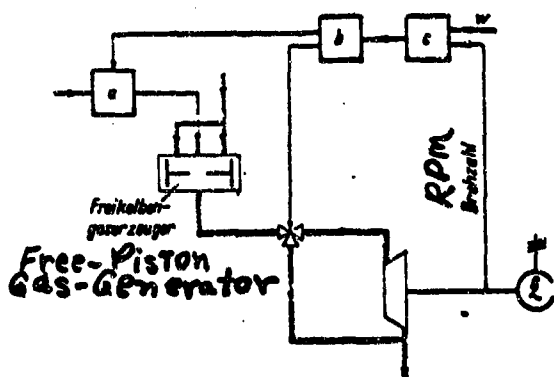


Fig. 13: Diagram for the Regulation of a Free-Piston Gas-Turbine Installation to Generate Current. a fuel system, b control device, c speed regulator.

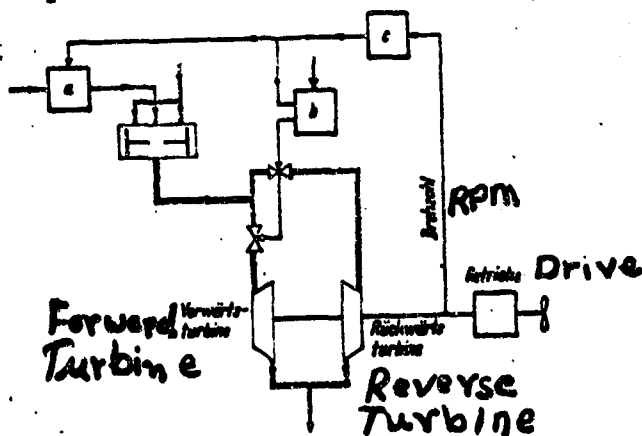


Fig. 14: Diagram for the Regulation of a Free-Piston Gas-Turbine Installation to Power a Ship with a Fixed-Pitch Propeller (symbols as in fig. 13).

2.2 Installations to Power Ships, Generators and Locomotives

Free-piston gas-turbines are employed in the operation of current generators, to power ships and to power locomotives. In installations for the operation of generators, a speed-regulating device adjusts the power output by changing the fuel supply or by releasing the gas supply (fig. 13). The dynamic behavior of the entire installation is unfavorably influenced by the inertia of the gas generator and the storage effect of the gas space in front of the turbine. In order to guarantee the shut-off safety in connection with the separation of a circuit, additional measures are, therefore, often necessary. The moment of inertia of the turbo-generator installation is either increased by a flywheel or the tachometer obtains a D-pulse. The conditions in the case of load increase are, naturally, especially unsatisfactory because an equivalent to the exhaust valve is missing. The descriptions that were given in chapter 1.3.2 also hold true for the regulation of the free-piston gas-turbine installations that are used to power ships. The problem of reverse motion is solved here of course, because of the relatively low gas temperature frequently with the use of a reverse turbine. The regulation that is used in installations such as this are shown in figure 14 [19] and [20]. The turbine output and the rotation direction of the screw is controlled from a central control panel. A dual valve distributes the gas flow to the forward and reverse turbines. In a certain position the resulting turbine output is zero. Adjustment to one or the other position brings about either forward or reverse motion. As the valves move toward one or the other end positions the performance is increased by the additional supply of fuel. In some cases a speed-regulating device is also provided which reduces the fuel supply in the event the number of revolutions is too high.

In the application of an adjustable-pitch propeller, two different designs in regulation are known. In the one case the central control equipment adjusts

the propeller first from the no-load position to either the forward or reverse position and, in this connection, the turbine output is increased by closing the air-return valve of the gas generator and by increasing the fuel supply [21], [22] and [23]. In the second case a speed-regulator holds the critical value according to the requirements that have been set to drive the ship, the revolutions of the turbine are kept constant by the effect of the control of the gas generator. The adjustment of the speed of the ship and its direction is accomplished with the adjustable-pitch propeller. The application of this installation in locomotives with direct mechanical transmission of power difference in the regulation ratios from those described in chapter 1.2.2 for the gas-turbine powered locomotives. It corresponds somewhat to that of the ship powered with a variable-pitch propeller.

Literature

1. Kirillov, J. J.: Regulation of Steam and Gas Turbines (Russ.) Moscow 1961, German Translation: Berlin: Technik Publishing House.
2. Brown, R. J. and Smith, A. W.: 500 kW Dual Fuel Gas-Turbine for Industrial Power, ASME-Paper No. 56-P-20.
3. White, A. C.: Design Features of New, Large Gas-Turbines for Power Generation AJEE-Paper No. 57-968.
4. Vogts, J.: Waste-Gas Turbines AEG-Gas-Turbine Installation to Operate Blast Furnace Blowers. MTZ, 20 (1959) Issue 6, p. 210-213.
5. Pfenniger, H.: The Brown Boveri Gas-Turbine with an Inlet Temperature of 750°C. Brown Boveri Report 47 (1960) No. 1, p. 35-64.
6. Anonym: Extension of American Power Range. Oil Engine and Gas Turbine. 27 (1959/60) no. 318, p. 384 to 386.
7.: A Lightweight 8000 HP Gas Turbine for Marine Propulsion. ASME-Paper No. 59-GTP-18.
8. Anonym: A British Company's Gas Turbine Progress. The Oil Engine and Gas Turbine (1958) No. 303, p. 284-285, No. 302, p. 233-236.
9. Anonym: A Canadian Plant of Medium Power. Oil Engine and Gas Turbine. 28 (1960/61) No. 320, p. 71-72.

10. Pope, A. W.: Design and Development of Four Lightweight High-Speed Marine Gas-Turbines for Electric Generator Drive. Proceedings of the Inst. of Mechanical Engineers, 172 (1958) No. 3, p. 301-319.

11. Mueller-Trimbush, K.: The First Waste-Gas Turbine Power-Plant in a German Metallurgical Plant. Steel and Iron, 79 (1959) Issue 8, p. 457-463.

12. Anonym: A New British Naval Gas-Turbine. Oil Engine and Gas Turbine, 27 (1959/60) No. 312, p. 141-146.

13. Lamb, J. and Birte, L.: The Auris Gas-Turbine Project. ASME-Paper, No. 58-GTP-12.

14. Anonym: Gas Turbines Power New Multy-Duty Naval Fast Patrol Boats. Oil Engine and Gas Turbines, 27 (1959/60) No. 313, p. 186-188.

15. McMullen, J. J.: The Trials and Maiden Voyage of the Gas-Turbine Ship John Sergante. Trans. Inst. Marine Eng. (1958) Issue 2, p. 45-70.

16. Van Nest, F. H.: The Control of a Marine Gas-Turbine. ASME-Paper, No. 58-GTP-10.

17. Huber, R.: Turbo Units of 1000 HP Powered by One or Several Free-Piston Generators. Presented at the International Congress for Combustion Machines, 1959 in Wiesbaden.

18. Moiroux, A. F.: The Free-Piston Engine Possibilities. ASME-Paper No. 58-OGP-7.

19. McMullen, J. J.: A Free-Piston Propulsion Plant for a Liberty Ship. ASME-Paper 55-OGP-14.

20. Anonym: Twin Gasifier Installation for Cargo Vessel Conversion. The Oil Engine and Gas Turbine, 27 (1959/60) No. 309, p. 27-30.

21. Anonym: British Free-Piston Engine Development. The Motor Ship (1960) March/April/May, p. 16-18.

22. Anonym: The Free-Piston Engined Cargo Vessel, "Rembrandt". The Oil Engine and Gas Turbine, 28 (1960/61) No. 322, p. 147-150.

23. Anonym: Dutch Free-Piston Engined Vessels in Service. The Oil Engine and Gas Turbine, 28 (1960/61) No. 326, p. 310-313.

24. Kruschik, J.: The Gas-Turbine. Vienna: Springer Publishing House 1960.

25. Warriek, T. J.: Control System for a 4500 HP Gas-Turbine Electric Locomotive. Trans. AIEE, 69 (1950) p. 508-513.

26. Pfenniger, H.: The Livorno and Fiumicino Gas Turbine Power Plants in Italy. MTZ (1957) No. 6, p. 189-193.

27. Eichelberg, G.: Free-Piston Generators. SBZ, 66 (1948) No. 48, p. 661-667, No. 49, p. 673-679.

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